An Overview of BFRL's Research on Cybernetic Building Systems

This overview of BFRL's cybernetic building systems (CBSs) major product is abstracted from a recently published report[1] that documents the economic impacts of past, ongoing, and planned BFRL research for developing and deploying CBSs in office buildings. The results of the economic impact assessment demonstrate that the use of CBS products and services will generate substantial cost savings to the owners, managers, and occupants of office buildings across the nation. The present value of cost savings nationwide expected from the use of CBS products and services in office buildings exceeds $1.1 billion in 1997 dollars. Furthermore, because of BFRL's role as a facilitator and developer of key CBS enabling technologies, CBS products and services are expected to become available commercially in 2003. Without BFRL's participation, the commercial introduction of CBS products and services would likely be delayed until 2010. Consequently, potential cost savings accruing to the owners, managers, and occupants of office buildings over the period 2003 until 2010 would have been foregone. These cost savings are $90.7 million in 1997 dollars. These cost savings measure the return on BFRL's CBS-related investment costs of approximately $11.5 million.

1 Cybernetic Building Systems: What They Are and What They Will Do

During the next ten years, building control companies, equipment and systems manufacturers, energy providers, utilities, and design engineers will be under increasing pressure to improve performance and reduce costs. One means of accomplishing this is through the development, adoption, and use of cybernetic building systems (CBSs) that integrate more and more building systems. Building systems targeted for incorporation into CBS products and services include energy management (e.g., heating, ventilation, and air-conditioning (HVAC) and lighting), fire (e.g., detection and fire fighting), security, fault detection and diagnostics, optimal control, the real-time purchase of electricity, and the aggregation of building stock for multi-facility operations. How these systems communicate, interact, share information, make decisions, and perform in a synergistic and reliable manner needs to be addressed on an industry wide basis if CBSs are to be successful and the U.S. is to obtain a significant share of the potential global market for such systems.

A CBS is defined as a multi-system configuration able to communicate information and control functions simultaneously and seamlessly at multiple levels. The configuration must also allow for two-way communication between the building(s) in which it is installed, utilities, and energy and service providers. The multiple levels of communication and control are based on the BACnet (***B***uilding ***A***utomation and ***C***ontrol ***net***works) layered protocol architecture.[2]

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[1] Chapman, Robert E. 1999. *Benefits and Costs of Research: A Case Study of Cybernetic Building Systems*. NISTIR 6303. Gaithersburg, MD: National Institute of Standards and Technology.

[2] For an overview of BACnet, see Section 2.1. For a description of BACnet's layered protocol architecture, see Bushby (Bushby, Steven T. 1997. "BACnet: A Standard Communication Infrastructure for Intelligent Buildings." *Automation in Construction* (Vol. 6): pp. 529-540).

BFRL is working towards a fully operational CBS being tested and deployed by 2002. To achieve this goal, BFRL is working with industry (e.g., equipment and systems manufacturers, and service providers), building professionals (e.g., owners, designers, and operators), trade associations, professional societies, standards organizations, university researchers, and other government agencies (e.g., General Services Administration and the Department of Energy). Strategic partnerships for the overall CBS research, development, and deployment effort is being patterned after the NIST BACnet Interoperability Testing Consortium. The BACnet Consortium is a cooperative research and development agreement between equipment manufacturers, facilities managers, and researchers aimed at developing interoperable building control equipment communicating with the BACnet protocol (see Section 2.1).

The overall CBS research, development, and deployment effort is built around six key projects (see Sections 2.1 through 2.6). In addition, the overall effort includes a full-scale demonstration of a CBS.

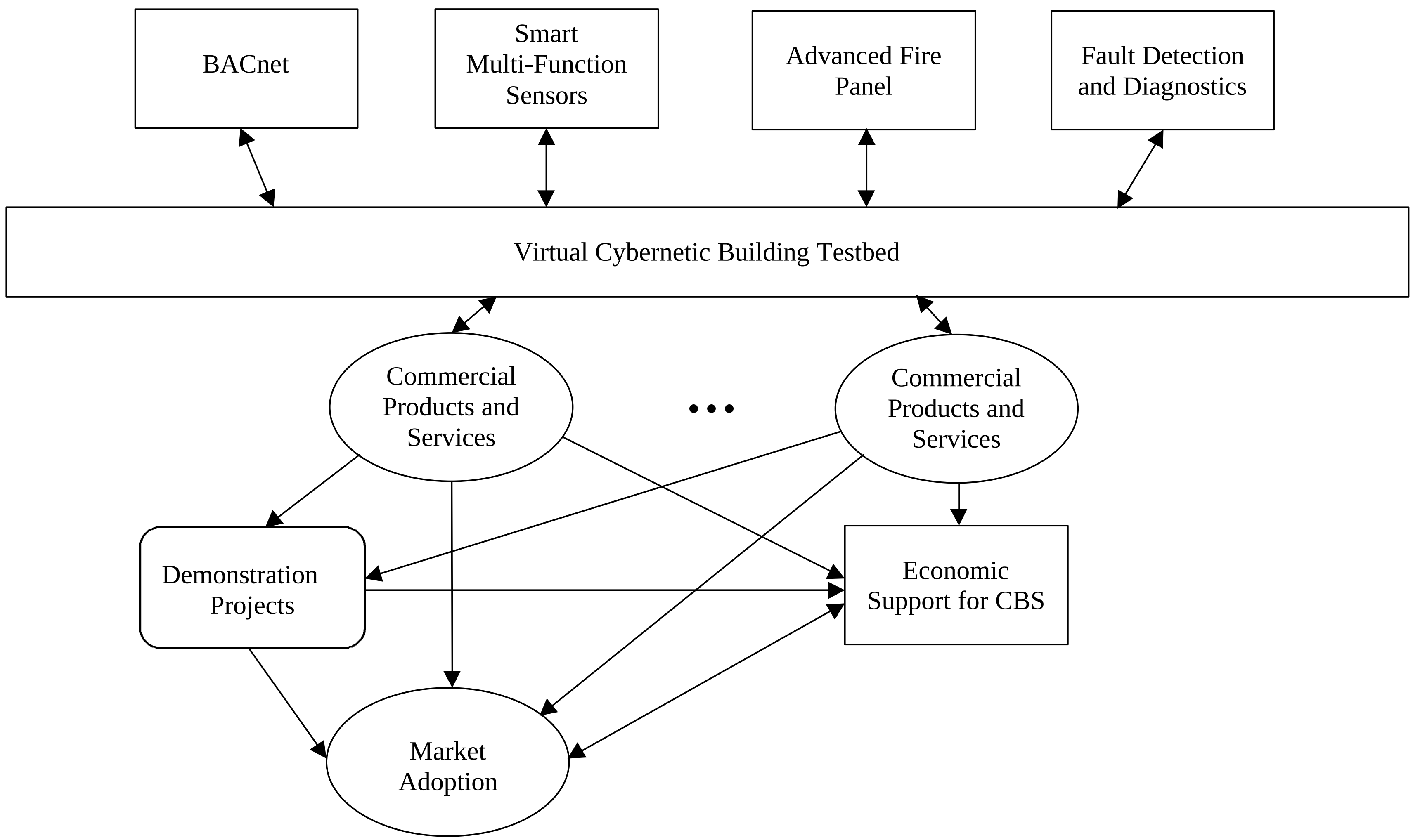
A schematic for how the six key projects fit together and how BFRL will work with industry to develop CBS products and services is shown in Figure 1. Each of the six key projects is represented by a rectangle in the figure. These activities are undertaken and funded primarily by BFRL. Those activities undertaken by the private sector are represented by ovals in the figure. Demonstration projects are a hybrid activity, involving a broad cross-section of participants; they are represented by the rectangle with rounded edges in the figure. Unidirectional arrows or bi-directional arrows (i.e., including a feedback mechanism) represent information flows between activities. Note that the Virtual Cybernetic Building Testbed provides the mechanism through which feedback between the upper tier of BFRL projects takes place. Figure 1 includes a vendor tier. Because many different vendors will develop and offer commercial products and/or services, the figure uses an ellipsis (**…**) to reflect the indeterminacy of the number of vendors in the vendor tier. Figure 1 shows the culmination of BFRL's efforts as the demonstration projects. Once the demonstration projects are completed, the private sector moves into a full-scale market adoption process. This process will evolve over a number of years as the CBS products and services diffuse throughout the marketplace.

Prior to the deployment of fully operational CBS products and services in 2002, BFRL will produce a series of intermediate products. These products are described briefly in the series of bullets that follow:

- Develop standard communication protocols for the open exchange of information among energy providers, utilities, energy management systems, fire detection/smoke control systems, security systems, elevator controls, and service providers.

- Develop enabling technologies, such as fault detection and diagnostic methods, a hierarchical framework for control decision making, advanced operating strategies for aggregated buildings, and the application of real time fire modeling in buildings.

Figure 1. Flowchart of CBS Research, Development, and Deployment Effort



- Develop advanced measurement technologies, including smart multi-functional sensors.

- Develop performance measures, standards, and evaluation tools for protocol compliance testing, real time monitoring, and the evaluation and documentation of CBS interactions.

- Construct a Virtual Cybernetic Building Testbed in the laboratory to facilitate the development and evaluation of new products and systems by manufacturers and external service providers.

- Develop a Consortium of manufacturers and service providers interested in producing, testing, demonstrating, and selling CBS products and services.

- Develop interoperability testing and certification programs to facilitate the development and introduction of CBS products and services into the marketplace.

- Conduct a prospective economic impact assessment of BFRL's CBS-related research, monitor outcomes, and conduct a follow-up economic impact assessment.

- Develop and demonstrate the integration of CBS products, services, and concepts on the system/subsystem level.

2 Key Components of BFRL's Research on CBS

2.1 Building Automation and Control Networks (BACnet)

Today's direct digital control systems (DDCs) employ proprietary communication protocols that prevent systems made by different manufacturers from communicating with each other. The problem dates from the 1980s when dropping prices and rising capabilities for computer-based technologies spurred the controls industry to use digital controls. To operate these controls requires exchanging data over a network, and individual DDC manufacturers solved the communication problems in different ways. The proliferation of proprietary systems has frustrated building owners' efforts to integrate innovative products from different DDC manufacturers in ways that best suit the unique needs of their building(s). Prior to the introduction of BACnet, building owners were forced to either forego potential cost savings due to systems integration or accept a proprietary system from a single vendor that could severely limit future expansion capabilities.

BACnet is a standard communications protocol for building automation and control systems developed under the auspices of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). BACnet provides a standard communications infrastructure interconnecting building automation and control devices made by different manufacturers. This makes it possible for building owners to obtain competitive upgrades to building control systems. In addition, BACnet makes possible the integration of building systems that currently stand-alone. In June 1995 BACnet was approved as an ASHRAE standard and, later, as an American national standard by the American National Standards Institute (ANSI). It has been selected as a European Community pre-standard by the European Committee for Standardization. Today, there are over 4,000 installed systems running BACnet in at least 16 countries.

In 1996, the largest federal building west of the Mississippi River, the Phillip Burton Federal Office Building in San Francisco, was selected by the General Services Administration (GSA) for the first large-scale demonstration of BACnet among multiple vendors.[3] BFRL provided technical assistance to GSA for this project including technical review of the control system design and specifications, laboratory testing of the BACnet capabilities of the products to be used in the building, and on site commissioning support. BFRL has also been collecting and analyzing network traffic data to document how BACnet performs in large control systems. Phase II of the project, retrofit of the control systems for the air handling units and over 1300 variable air volume (VAV) box controllers, was completed in 1998 and the multi vendor BACnet control system is fully operational. Phase III when underway will expand the BACnet system to a new central plant facility and connect the control system in this building with other GSA buildings. This will provide centralized access to energy consumption and system performance data, and prepare GSA for aggregating utility loads in a deregulated marketplace.

BACnet work is expanding beyond the HVAC realm. BFRL is working with the National Electrical Manufacturers Association (NEMA) and the National Fire Protection Association (NFPA) to extend BACnet to fire protection products. NEMA has endorsed BACnet as the industry's recommended method of integrating security and fire alarm systems with other building control systems. The first commercial BACnet fire system products will be introduced within the next two years. New features are being added to the protocol that will enhance the use of BACnet in life-safety systems. For example, some day “smart elevators” may be able to tap into HVAC control and fire detection systems so, if there is a fire, elevators can be used to help evacuate people in a safe and efficient manner.

To date, BFRL has entered into cooperative research and development agreements with 22 partners to develop interoperable building control equipment that communicates using the BACnet protocol. The objective of the consortium is to assist the member companies in developing products that conform to the BACnet standard and to develop conformance-testing tools and procedures that can be used to establish an industry-run certification program. BFRL has developed test methods and software testing tools and provided facilities for member consortium companies to bring their prototype products together for testing.

The Visual Test Shell (VTS) is a BFRL developed software tool for testing building control products for conformance to the BACnet standard. VTS is now being used by

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[3] Applebaum, Martin A., and Steven T. Bushby. 1998. “The 450 Golden Gate Project: The World’s First Large-Scale Use of BACnet.” *ASHRAE Journal* (July): pp. 23-30.

manufacturers who are developing BACnet products. The testing procedures implemented in VTS have become the basis for a draft addendum to the BACnet standard that defines a conformance test suite. A revised version of this tool, which runs in a Windows95 or WindowsNT environment, was released in 1998. Development of the testing tool will continue in parallel with an ASHRAE addendum to the BACnet standard which will define conformance-testing procedures for BACnet.

2.2 Smart Multi-Function Sensors

The United States currently spends billions of dollars annually to install and maintain systems in buildings to assure safety from unwanted fires. A major opportunity for cost savings is to reduce both these expenditures and fire-related losses through the introduction of new products. Smart multi-function sensors will permit fire and indoor air quality (IAQ) sensor designers to demonstrate the feasibility of new concepts, to provide the critical link between sensor input and output required for meaningful numerical simulations, and to improve the reliability and performance of fire detection systems.

Test protocols and certification processes have been developed to accommodate specific fire sensor technologies. In the past, the sources used in these test methods were optimized for a unique fire or smoke property to quantify detector response. Very little has been done to determine the impact of test methods on the development of innovative IAQ sensors. To improve detection sensitivity and reduce inappropriate responses, the industry has developed new sensor designs based on the measurement of different aspects of the fire source, or on specific combinations of sensors that can help in distinguishing a real fire from an interfering background signal. Existing test methods are unable to evaluate and quantify the performance of the new sensing systems needed for monitoring and predicting the changing environment as part of a CBS.

BFRL is working with the IAQ and fire sensing industries to identify the state of the technology, the opportunities for sharing information among fire and other building control systems, and the advantages and barriers hindering the adoption of emerging technologies (e.g., micro-electronic gas sensor arrays and wireless communication sensing). Emerging sensing technologies for duct and ceiling air velocity and pressure differences between adjacent rooms will also be examined. Efforts will be aimed at demonstrating the advantages of multi-function sensors (e.g., using the output of an existing CO_2/IAQ sensor to help define the fire/non-fire state or the movement of fire gases) and multi-sensor (e.g., using the output from CO, temperature, and smoke sensors to distinguish nuisance sources from threatening fires). This will include the use of such sensors for improving the reliability and performance of fire detection systems through earlier detection of small fires, and the reduction in both false negatives (i.e., reported fires that do not exist) and false positives (i.e., unreported fires). A standard means for evaluating the response of fire and IAQ sensors, including exposure to nuisance sources, will be developed and offered for adoption to industry. Water vapor condensation is thought to be a major source of false negatives, but is also a useful marker for the environmental state. A means for assessing a sensor’s response to water vapor will be explored. Full-scale room tests will be conducted to determine the environment adjacent to the detector, and the fire-emulator/detector-evaluator will be programmed to reproduce those conditions.

2.3 Advanced Fire Detection and Alarm Panels

As noted earlier, the United States currently spends billions of dollars annually to install and maintain systems in buildings to assure safety from unwanted fires. A major opportunity for cost savings is to reduce both these expenditures and fire-related losses through the introduction of new products. Advanced fire detection and alarm panels have the potential to revolutionize the way building fires are detected, located, and fought by fire-fighting personnel.

Advanced fire detection and alarm panels, when fully developed and deployed, will isolate the location of a fire in a building and predict the short and long term behavior and effects of fire growth and smoke spread in the building. Development and deployment of the advanced fire detection and alarm panels will be facilitated through a strategic coalition with the detection industry, the National Electrical Manufacturers Association, and the National Fire Protection Association.

To date, BFRL has developed an advanced model of fire growth and smoke spread in buildings. As sensor use in buildings becomes more widespread, it is possible to use this information as input to the BFRL model to detect and predict the evolution of a fire in a building. Work is currently underway to orient the BFRL model so the inputs are based on building plans, the contents of the buildings, and sensor data. As a result, model inputs can be specified both for current building systems and for more advanced systems (e.g., those using the BACnet protocol). As the sensor suite becomes more extensive and provides more information, model predictions can be refined to provide greater detail and more reliable predictions for longer time intervals.

The advanced fire detection and alarm panels and their associated models and algorithms will provide continuous estimates of the state of a building, enabling smart sensing to reduce false alarms and to produce both short and long term predictions for purposes of escape and rescue. For very large facilities, this would enable a measured response so those incidents can be isolated and contained without general interruption of business. It is important to verify the algorithms developed for the advanced fire detection and alarm panels and to test them under a variety of adverse conditions to minimize false negative reports. Elimination of both false negatives and false positives will be a high priority. The algorithms employed will use sensor data to start the predictive models, and then refine the prediction, as additional information becomes available. An important aspect of this approach is the knowledge of what information sensors are reporting. For example, analog information is available from the sensors, but a better understanding is needed of how different sensors respond to the ambient environment. This effort will require development of a standard test method to obtain these data for use in the sensor-driven models and to quantify the response of single and multi-function building sensors to thermal, flow, gas, and particulate loadings.

2.4 Fault Detection and Diagnostic Systems with Hierarchical Controls

Today's building energy management systems have the capability to monitor and log operating data for thousands of measurement and control points. These capabilities routinely exceed the capabilities of building owners and operators to process and understand the data. Consequently, HVAC equipment frequently operates under the influence of faults that go undetected. The faults lead to energy waste, occupant discomfort, and shorter equipment life. Building energy management systems need to be equipped with intelligent fault detection and diagnostic (FDD) tools to enable building operators to ensure that HVAC systems are operating as expected. These FDD tools will detect problems (i.e., faults) as they occur, determine what component or system is failing or has failed, and recommend maintenance and repair procedures. These FDD tools can then be incorporated into either the building energy management system, the building equipment, or into stand-alone systems dedicated to fault detection and diagnostics.

In 1998, BFRL completed the development of a prototype FDD Test Shell. The FDD Test Shell is a platform based on Microsoft Windows dynamic data exchange (DDE) that facilitates the integration of FDD modules (e.g., data, reference models, and possibly multiple FDD methods) developed in any application development environment that supports DDE. The FDD Test Shell can accept data from an experimental rig, a simulation model, or a file containing columns of data. Part of this data might be used to drive reference model modules that provide expected values of variables or parameters to the FDD Test Shell. The differences (i.e., residuals) between the data and the reference model values are computed automatically and made available to FDD methods that operate on the residuals and present results on their individual user interfaces. FDD methods can also access the unprocessed data provided to the Test Shell by the data source. The modular architecture provides a structured way for researchers to share data, models, and methods. Annex 34 participants[4] have adopted the FDD Test Shell as a working tool, and seven countries, including 11 separate institutions, have committed to use the FDD Test Shell or to test their FDD methods with shared data sets.

During 1999, BFRL will extend the FDD Test Shell to include a module for evaluating and comparing the output of FDD methods. In addition, a front-end program will be written that will allow BFRL's HVACSIM$^+$ program[5] to be a data source for the FDD Test Shell. Finally, effort will begin on integrating FDD methods into a hierarchical framework that coordinates operational information from various subsystems (e.g., VAV boxes and air handling units). In its completed form, the FDD Test Shell is envisioned as a platform that will accept data from various sources, allow different modules to be written in a variety of programming languages, and synthesize information obtained from the various FDD methods in a logical manner.

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[4] International Energy Agency Annex 34 Committee on Computer-Aided Evaluation of HVAC System Performance: The Practical Application of Fault Detection and diagnostics Techniques in Real Buildings.

[5] Park, Cheol, Daniel R. Clark, and George E. Kelly. 1985. "An Overview of HVACSIM$^+$, A Dynamic Building/HVAC/Control Systems Program." *Proceedings of the 1st Annual Building Energy Simulation Conference*: pp.175-185.

By 2002, the knowledge gained by integrating and synthesizing multiple FDD methods in the FDD Test Shell will be used to develop a hierarchical architecture for CBSs that will allow various CBS functions (e.g., energy management, fire detection, elevator control, system optimization, building aggregation, and the real time purchase of electricity) to work together. Both expert systems and fuzzy logic will be studied to address the problem of "command fusion" (i.e., command coordination). The latter approach converts command fusion into a logic of graded preferences with each control function portrayed as an agent expressing "preferences" that suggest which command to apply. Fuzzy operators are used to combine the various preferences and to generate a single control choice based on multiple trade-offs. Fuzzy logic can also be used to develop "meta-rules" to describe and implement strategies for high-level control arbitration.

BFRL is initiating work with industrial partners and other control manufacturers to verify the proper performance of prototype FDD products. In conjunction with this testing, BFRL will begin an FDD demonstration project at the Phillip Burton Federal Office Building or other suitable site. By 2001, FDD methods are expected to begin to be implemented in energy management and control system products. By 2002, some of these methods are projected to begin to be implemented in other building control products.

2.5 Virtual Cybernetic Building Testbed

With the increasing pressure to integrate more and more building control systems and services, there is a need to be able to test and evaluate the complex interactions that are likely under both normal and adverse (e.g., emergency) operating situations. In addition, there is a need to assist control manufacturers and service providers in the development, testing, and certification of new products. Due to the complexity of the systems involved and the need to maintain a comfortable and safe building occupant environment at all times, these tasks can not be accomplished using real buildings. However, these tasks can be done through simulation/emulation. The establishment of a Virtual Cybernetic Building Testbed (VCBT) will enable manufacturers to bring the actual control products under development, obtain assistance in testing and evaluating their performance, and perform interoperability tests with other manufacturers.

When fully deployed in 2001, the VCBT will consist of a variety of simulation models emulating the performance of a typical CBS. The simulation models will be interfaced with real state-of-the-art and prototype BACnet compliant control systems to provide a hybrid software/hardware testbed. The testbed will be used by NIST researchers, control manufacturers, service companies, and software developers to develop and evaluate control strategies and control products that use the BACnet communication protocol. The VCBT is designed to emulate the performance of both fault free and fault containing building heating and cooling equipment, different HVAC systems, and the building shell. In addition, lighting, vertical transport systems, and other services would be emulated. An advanced graphical user interface is being developed along with remote accessibility to the VCBT through various communication interfaces, including telephone and the Internet.

The VCBT will combine BFRL’s extensive experience with the modeling and simulation of buildings, HVAC systems, controls, and fires with the Manufacturing Engineering Laboratory's (MEL’s) expertise in the area of systems integration, object oriented programming, the use of a Common Object Request Broker Architecture (CORBA), advanced information models and data bases, and the Virtual Reality Modeling Language (VRML). It will make use of MEL’s ATM (asynchronous transfer mode) network to exchange information among the various VCBT components in real time and will allow for both on-site and remote use of the VCBT by NIST customers.

The development and deployment of the VCBT is divided into four phases. Phase I, which was completed in 1998, involves the development of an HVAC emulator to simulate the performance of a VAV air handling unit, three VAV boxes, and three building zones using BFRL’s HVACSIM$^+$ program. Phase II, which will be completed in September 1999, involves development of a building shell emulator, a fire emulator, a more complex HVAC emulator, a building/HVAC Product Model, and a VRML based interactive VCBT display. The various VCBT components, which will be in different NIST locations, will use the CORBA paradigm to provide a real time, distributed emulation environment based on message passing between objects and client-server programming. The last two phases will involve the enhancement of the VCBT front-end and the expansion of the VCBT to include the emulation of additional building services, fault containing systems, and other services likely to be provided by outside service companies.

The VCBT will be used by researchers at NIST and other organizations to study the complex interactions that occur as a result of integrating different building services and systems. Of particular interest is the impact of integrating fire detection, smoke control, transportation, HVAC, and energy management systems on life safety. The extension of the BACnet protocol to cover lighting, fire detection, transportation, and other services will be facilitated by the availability of the VCBT as a testbed for testing and evaluating changes to the BACnet standard. The VCBT will also be used by manufacturers of building controls and future CBS products to develop and test algorithms, evaluate the performance of new products, and perform interoperability testing with other manufacturers. The existence and use of the VCBT by newly developing service companies will facilitate the development of new building services, such as fault detection and diagnosis, automated commissioning, building system optimization, and predictive maintenance.

The VCBT will allow BFRL and ASHRAE to more quickly and reliably extend the BACnet standard to cover non-HVAC services. By helping building researchers better understand the interaction between different building control systems, the VCBT will facilitate the development of new national and international standards for integrating these systems in a manner that will enhance life safety, increase reliability, and result in more efficient operation and enhanced building system performance.

2.6 Economic Support for Cybernetic Building Systems

CBS products and services are one means to improve the performance of building systems and to reduce the costs of these systems. But investments in and the use of CBS products and services will be forthcoming only if industry perceives that the economic benefits outweigh the costs of using such products and services. Being able to demonstrate net economic savings from using CBS products and services will encourage their acceptance and use. Economic support for the overall CBS effort addresses the need for information on the economic consequences of investing in CBS products and services in two distinct ways.

First, the Office of Applied Economics (OAE) will conduct an *ex ante* (i.e., prospective) economic impact assessment of BFRL's CBS-related research, monitor outcomes, and conduct a follow-up economic impact assessment. Readers interested in the results of the *ex ante* economic impact assessment are referred to NISTIR 6303.[6] OAE will also design and create a database for compiling information on CBS-related impacts. Once the database is in place, OAE will monitor outcomes and compile information on CBS-related impacts in preparation for the follow-up economic impact assessment.

Second, OAE will develop user-friendly, decision-support software to facilitate the economic evaluation of CBS products and services and the identification of cost-effective levels of investment in these products and services. To make cost-effective choices for investments in CBS products and services, decision makers must have data on benefits and costs associated with these products and services, information on who bears the costs and reaps the benefits, and tools (methods and software) for measuring those benefits and costs. Having a package of economic tools that helps users and stakeholders identify and measure the benefits and costs of choosing between CBS products and services and traditional products and services will accelerate the introduction and acceptance of CBS products and services in the U.S. and abroad. Thus, OAE will produce an integrated software package providing life-cycle cost (LCC) measurement capabilities for evaluating CBS products and services. To assure industry acceptance of the software package, it will be made consistent with ASTM's LCC standard practice, E 917. Once the software package has been finalized, OAE will seek out a private-sector collaborator to market, distribute, and maintain the decision support software package.

[6] Chapman, *A Case Study of Cybernetic Building Systems.*